

Scalar Mesons and the Valence Quark Model



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- The meson spectra have been successfully described in terms of quark-antiquark pairs, however there are problems for the case of the light scalar mesons
- A similar situation has recently appeared in the open-charm mesons

Light scalar mesons

Too many resonances observed:

- 2 isovectors $I=1$: $a_0(980)$, $a_0(1450)$
- 3 $I=1/2$ states : $K_0(800)$, $K_0(1430)$, $K_0(1950)$
- 10 isoscalars $I=0$: $f_0(600)$, $f_0(980)$, $f_0(1200-1600)$, $f_0(1370)$, $f_0(1500)$,
 $f_0(1710)$, $f_0(1790)$, $f_0(2020)$, $f_0(2100)$, $f_0(2200)$

Masses very difficult to accommodate as quark-antiquark states
Decays not compatible with a simple quark-antiquark structure

$$q\bar{q} [J^{PC} = 0^{++}] \Rightarrow S = 1 = L$$

- **S=0**

$$E(L=1) - E(L=0) = \left\{ \begin{array}{l} h_1(1170) - \eta(550) \\ h_1(1595) - \eta'(958) \\ h_c(3526) - \eta_c(2980) \end{array} \right\} \approx 0.5 - 0.6 \text{ GeV}$$

- **S=1**

$$[L=0] \left\{ \begin{array}{l} \rho(770) \\ \omega(782) \end{array} \right\} \Rightarrow [L=1] \text{ X}(J^{++}) \approx 1.3 - 1.4 \text{ GeV}$$

- What do we observe experimentally?

$(L=1, S=1)$	I=0	I=1/2	I=1
J=0	$f_0(600)$ $f_0(980)$	$K_0(800)$	$a_0(980)$
J=1	$f_1(1285)$	$K_1(1270)$	$a_1(1260)$
J=2	$f_2(1270)$	$K_2^*(1430)$	$a_2(1320)$

Open charm mesons

Strange

$D_{sJ}^*(2317)$

- $J^P=0^+$
- P -wave $c\bar{s}$ state ~ 2.48 GeV
- Width < 4.6 MeV

$D_{sJ}(2460)$

- $J^P=1^+$
- P -wave $c\bar{s}$ state ~ 2.55 GeV
- Width < 5.5 MeV

Non-strange

$D_0^*(2308)$

- $J^P=0^+$
- P -wave $c\bar{n}$ state ~ 2.46 GeV
- Width ~ 276 MeV

What makes these mesons special systems?

The Fock space is larger than simple quark-antiquark components

Neglecting explicit gluon degrees of freedom, a $B=0$ system may be described as:

$$|B = 0\rangle = \Omega_1 |q\bar{q}\rangle + \Omega_2 |q\bar{q}q\bar{q}\rangle + \dots$$

	$q\bar{q} (\sim 2m_q)$	$q\bar{q}q\bar{q} (\sim 4m_q)$	
Negative parity	$0^-, 1^- (\mathbf{L=0})$	$0^-, 1^- (\ell_i \neq 0)$	$\Omega_2 \sim 0$
Positive parity	$0^+, 1^+, 2^+ (\mathbf{L=1})$	$0^+, 1^+, 2^+ (\ell_i = 0)$	$\Omega_2 \sim \Omega_1$



Unquenching may be important for P -wave mesons!

Evaluating the influence of higher Fock-space components

$$H = H_0 + H_1 \quad ; \quad H_0 = \begin{pmatrix} H_{q\bar{q}} & 0 \\ 0 & H_{qq\bar{q}\bar{q}} \end{pmatrix} \quad ; \quad H_1 = \begin{pmatrix} 0 & V_{q\bar{q} \leftrightarrow qq\bar{q}\bar{q}} \\ V_{q\bar{q} \leftrightarrow qq\bar{q}\bar{q}} & 0 \end{pmatrix}$$

H_0 : Interacting potential

- Confinement: Linear screened potential
- One-gluon exchange: Standard Fermi-Breit potential
Scale dependent α_s
- Boson exchanges: Chiral symmetry breaking
Not active for heavy quarks

Parameters determined on the NN interaction and meson spectroscopy

$$H_1 = \langle q_1 q \bar{q} \bar{q}_2 | V | q_1 \bar{q}_2 \rangle = C_q \Rightarrow \begin{cases} \text{light scalars} \begin{cases} q=n \rightarrow C_n \\ q=s \rightarrow C_s \end{cases} \\ \text{open charm } q=n \rightarrow C_n' \end{cases}$$

Solving the Schrödinger equation for H_0

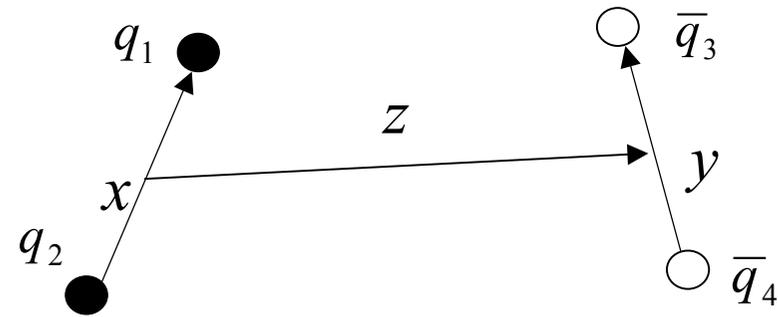
$H_{q\bar{q}}$: Standard Numerov algorithm

$H_{q\bar{q}q\bar{q}}$: Variational method

$$\Psi(\vec{x}, \vec{y}, \vec{z}; \alpha) = \sum_k \beta_k C_k(12,34) S_k(12,34) F_k(12,34) R_k(\vec{x}, \vec{y}, \vec{z}; \alpha)$$

Radial wave function as a combination of generalized gaussians $R_k(\vec{x}, \vec{y}, \vec{z}; \alpha) \propto \text{Exp}(-\alpha_{ij} \vec{x}_i \vec{x}_j)$

- Well defined permutation properties (SS, AA, AS, SA)
- $L=0$ (relative angular momenta $\ell_i \neq 0$)
- Positive parity



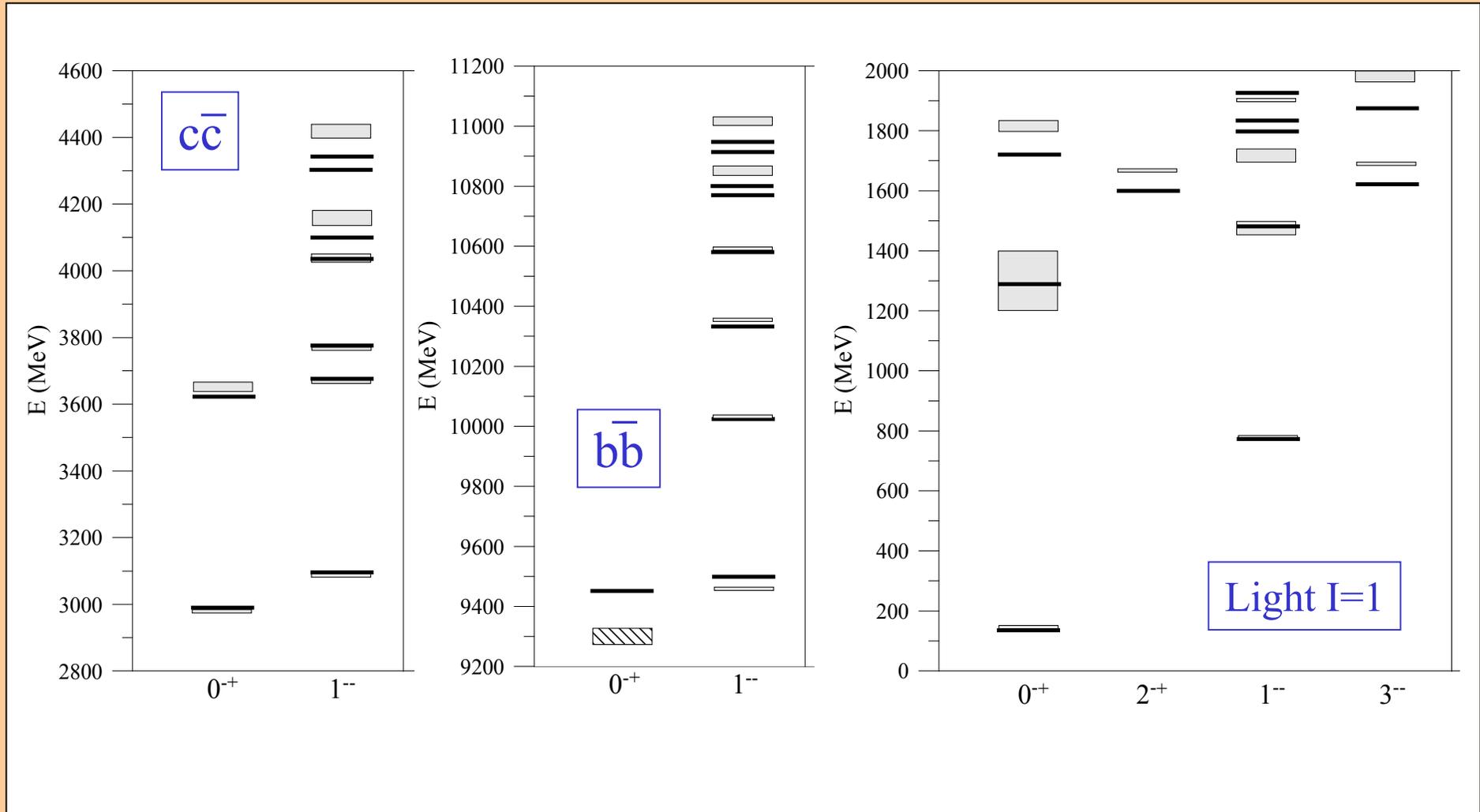
$$S_k(12,34) \quad F_k(12,34)$$

$$\left. \begin{aligned} S_k(12,34) &= \left[(S_1 S_2)_{S_{12}} (S_3 S_4)_{S_{34}} \right]_{S_T} \\ F_k(12,34) &= \left[(I_1 I_2)_{I_{12}} (I_3 I_4)_{I_{34}} \right]_{I_T} \end{aligned} \right\} \rightarrow \begin{pmatrix} \text{SS, SA} \\ \text{AS, AA} \end{pmatrix}$$

$$C_k(12,34)$$

$$3 \otimes 3 \otimes \bar{3} \otimes \bar{3} = \begin{cases} 6 \otimes \bar{6} = 1 \oplus 8 \oplus 27 & (\text{SS}) \\ \bar{3} \otimes 3 = 1 \oplus 8 & (\text{AA}) \end{cases}$$

Negative parity two-body spectroscopy



Scalar mesons as quark-antiquark states: H_0

I=0			I=1		
CQM (MeV)	State	Exp. (MeV)	CQM (MeV)	State	Exp. (MeV)
648	$f_0(600)$	400-1200	1079	$a_0(980)$	984.7 ± 1.2
	$f_0(980)$	980 ± 10	1626	$a_0(1450)$	1474 ± 19
1376	$f_0(1.2-1.6)$	1400 ± 200			
1463	$f_0(1370)$	1200-1500			
	$f_0(1500)$	1507 ± 5			
	$f_0(1710)$	1714 ± 5			
1782	$f_0(1790)$	1790^{+40}_{-30}		$K^*_0(800)$	≈ 800
1915	$f_0(2020)$	1992 ± 16	1273	$K^*_0(1430)$	1412 ± 6
	$f_0(2100)$	2103 ± 7	1797	$K^*_0(1950)$	1945 ± 22
2224	$f_0(2200)$	2197 ± 17			
2351	$f_0(2330)$	2337 ± 14			

Light scalars

Four-quark components: H_0

I=0

$q\bar{q}$ (MeV)	$q\bar{q}q\bar{q}$ (MeV)	State	Exp. (MeV)
648	-	$f_0(600)$	400-1200
-	949	$f_0(980)$	980 ± 10
1376	-	$f_0(1.2-1.6)$	1400 ± 200
1463	-	$f_0(1370)$	1200-1500
-	1525	$f_0(1500)$	1507 ± 5
-	-	$f_0(1710)$	1714 ± 5
1782	-	$f_0(1790)$	1790^{+40}_{-30}
1915	-	$f_0(2020)$	1992 ± 16
-	2015	$f_0(2100)$	2103 ± 7
2224	-	$f_0(2200)$	2197 ± 17
2351	-	$f_0(2330)$	2337 ± 14



I=0 (MeV)		
$nn\bar{n}\bar{n}$	$ns\bar{n}\bar{s}$	$ss\bar{s}\bar{s}$
949	1525	2015

I=1 (MeV)		I=1/2 (MeV)	
$nn\bar{n}\bar{n}$	$ns\bar{n}\bar{s}$	$nn\bar{n}\bar{s}$	$ns\bar{s}\bar{s}$
1308	1522	1295	1802

$H_0 + H_1$

I=0

CQM (MeV)	State	Exp. (MeV)
568	$f_0(600)$	400-1200
999	$f_0(980)$	980 ± 10
1301	$f_0(1.2-1.6)$	1400 ± 200
1465	$f_0(1370)$	1200-1500
1614	$f_0(1500)$	1507 ± 5
-	$f_0(1710)$	1714 ± 5
1782	$f_0(1790)$	1790^{+40}_{-30}
1900	$f_0(2020)$	1992 ± 16
2044	$f_0(2100)$	2103 ± 7
2224	$f_0(2200)$	2197 ± 17
2351	$f_0(2330)$	2337 ± 14

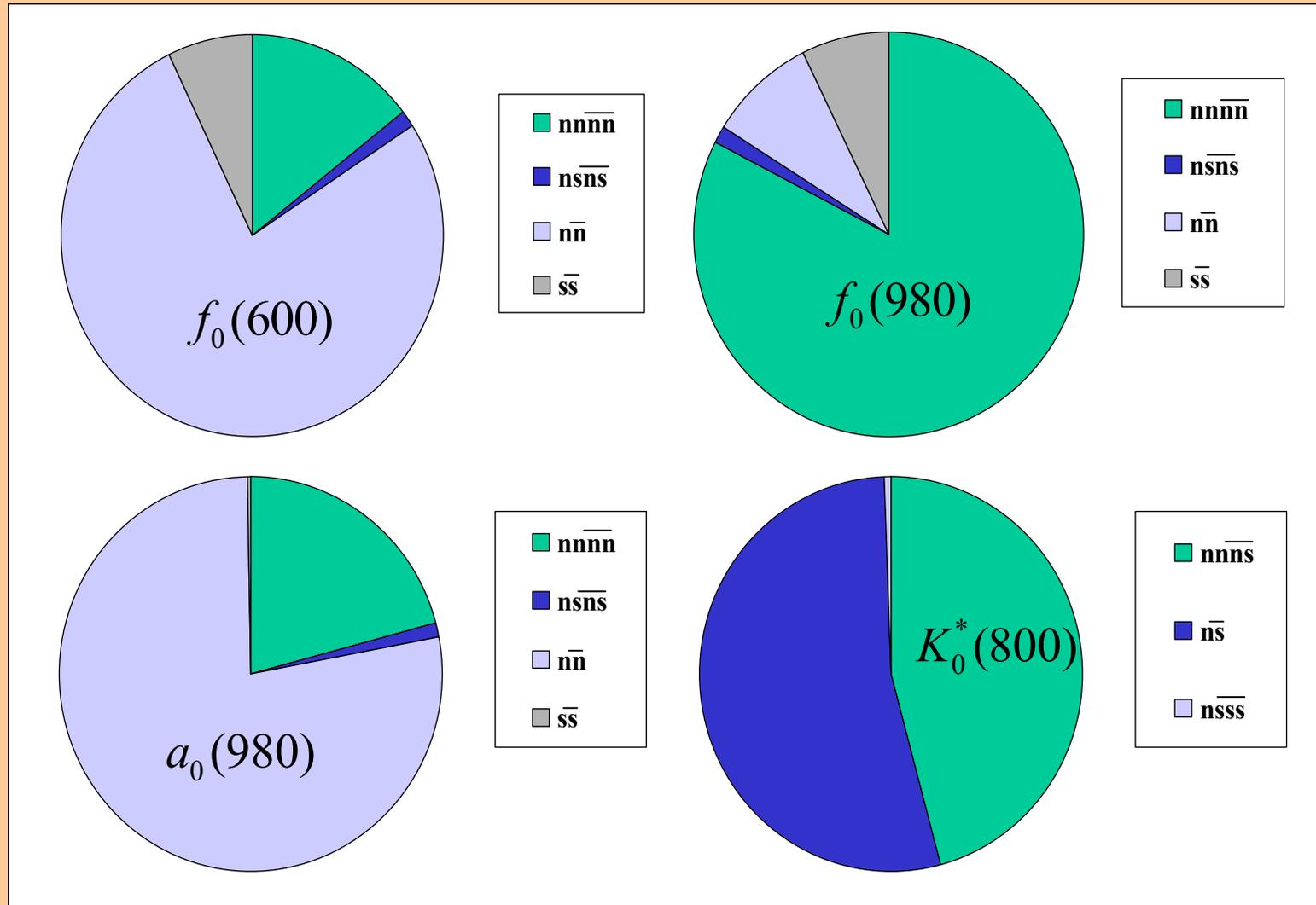
I=1

CQM(MeV)	State	Exp (MeV).
985	$a_0(980)$	984.7 ± 1.2
1381	$a_0(1450)$	1474 ± 19
1530		

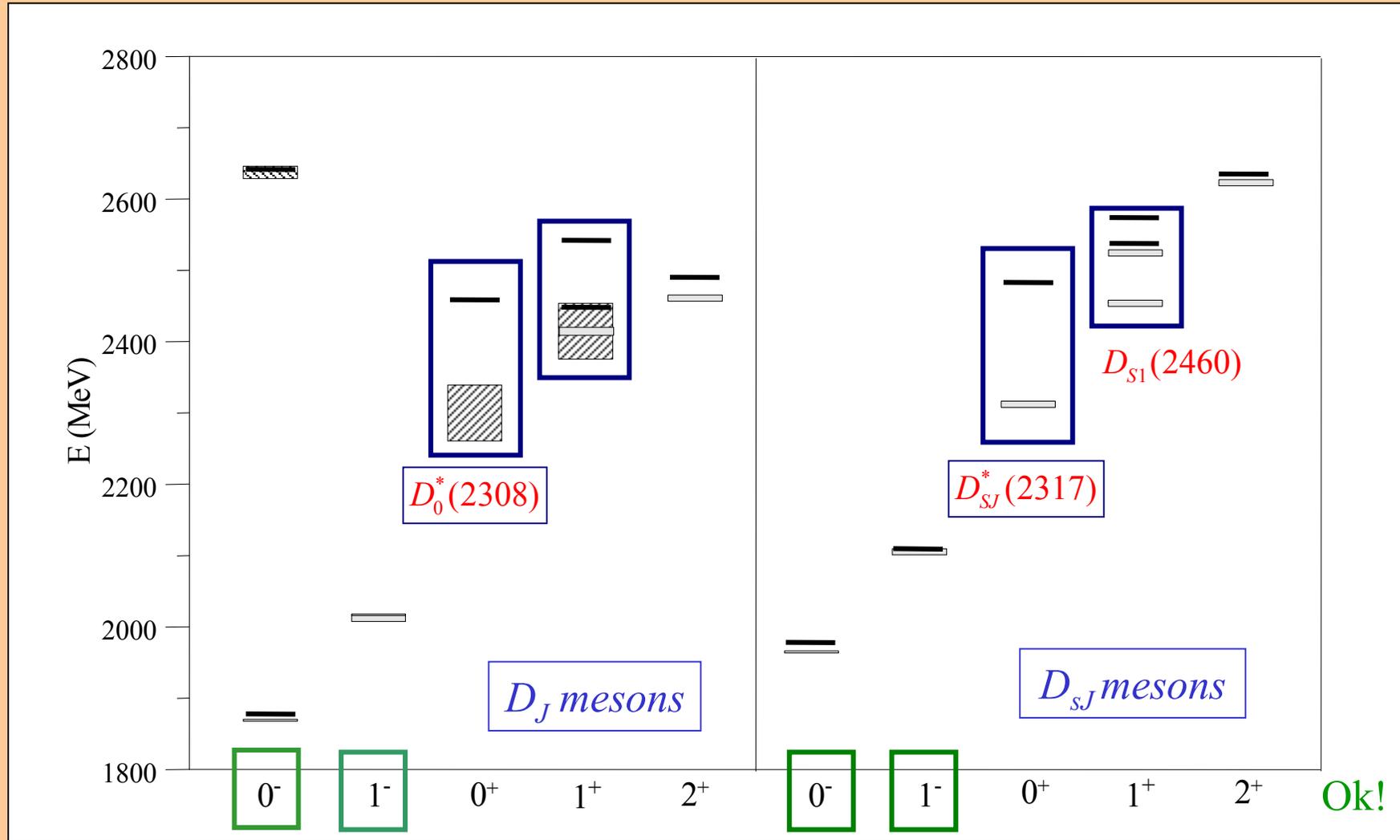
I=1/2

CQM (MeV)	State	Exp (MeV)
1113	$K^*_0(800)$	≈ 800
1440	$K^*_0(1430)$	1412 ± 6
1784	$K^*_0(1950)$	1945 ± 22
1831		
2060		

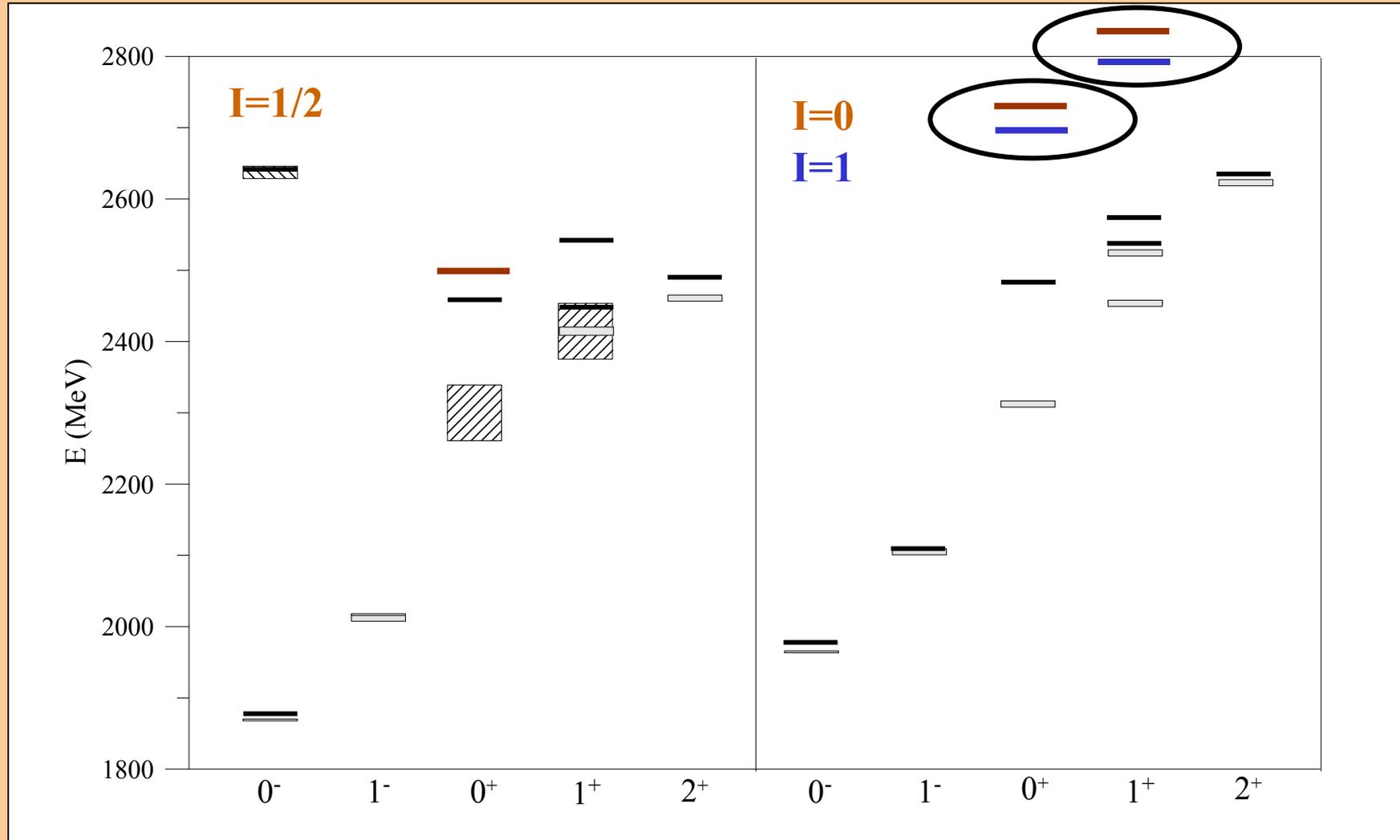
Involved wave-function structure



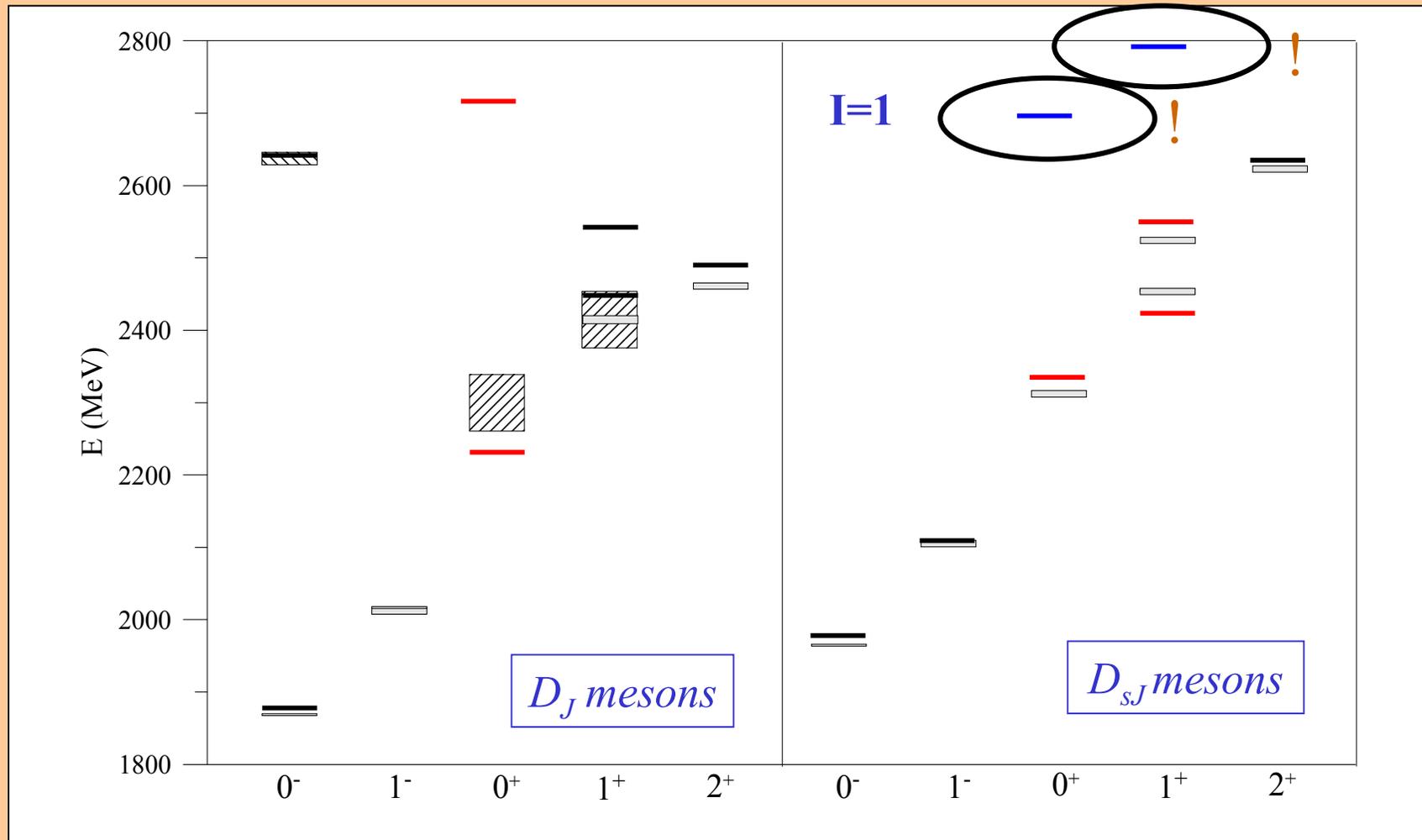
D_J and D_{sJ} mesons as quark-antiquark states: H_0



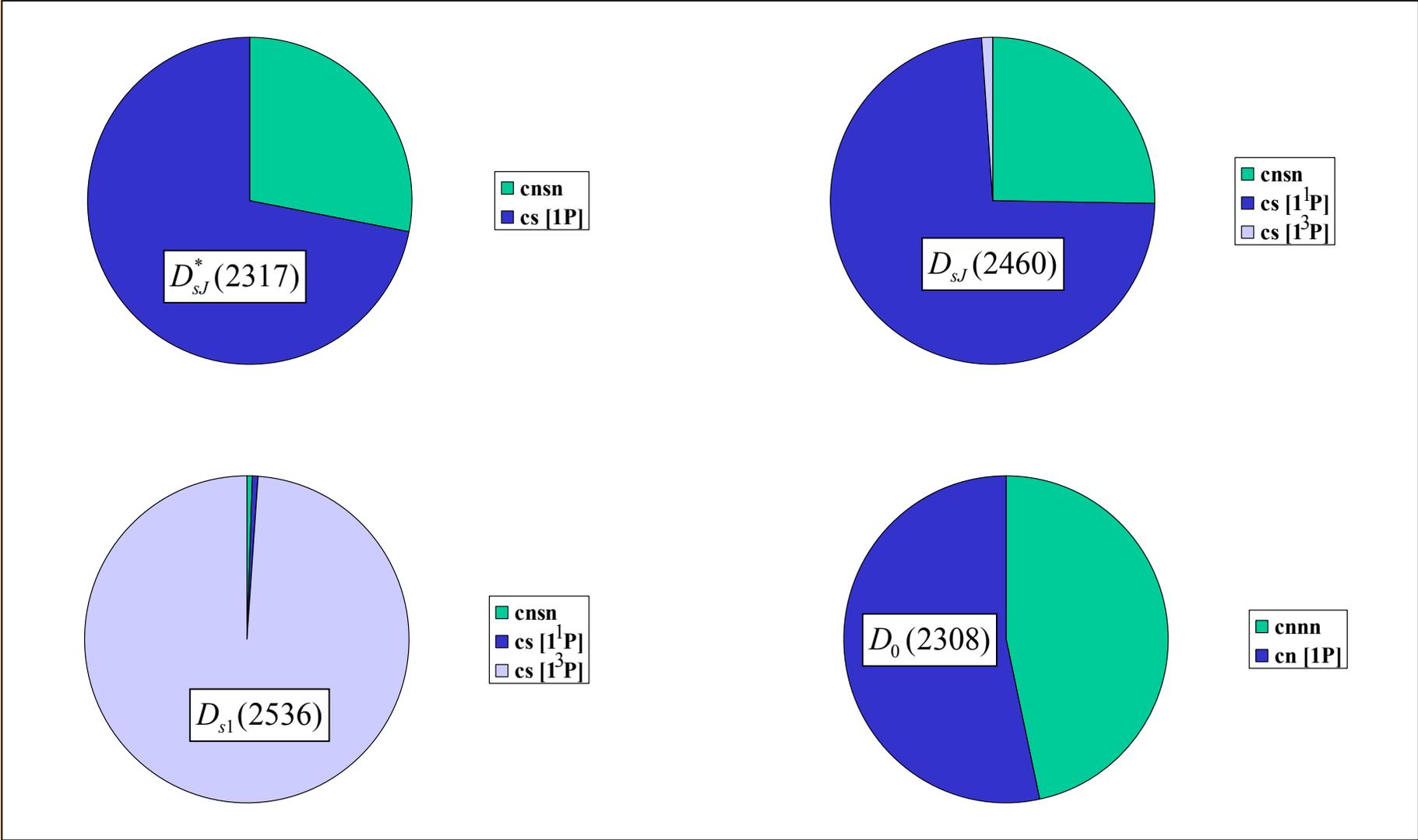
Four-quark components: H_0



$$H_0 + H_1$$



Involved wave-function structure



Summary

- The description of P -wave mesons within the valence quark model may require higher-order Fock space components: four-quark vectors.
- Any conclusion about their importance should be obtained treating two- and four-quark components altogether.
- Light scalar and open-charm mesons (D_J and D_{sJ}) are well reproduced within a potential model considering two and four-quark components.
- Although not discussed in this talk, not only spectroscopic properties but also decay widths are improved with respect to standard quark-antiquark models.

Phys. Rev. D 72, 034025 (2005)

Eur. Phys. J. A 19, 383 (2004)

J. Phys. G 31, 481 (2005)

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- It was a general belief within the hadron physics community that the valence quark model provided a proper description of the low-energy hadron spectroscopy: mesons and baryons
- With the advent of the pentaquark stuff the early 21th century has confronted different feelings

*Using Frank Close papers we moved from
The end of the constituent quark model? (hep-ph/0311087)*

to

Vanishing pentaquarks. Nature 435, 287 (2005)

- The most important problems of the valence quark model appeared for the understanding of the light scalar mesons
- This situation has been recently extended to the open charm mesons

Glueballs? : Lattice QCD

How to describe a scalar glueball?

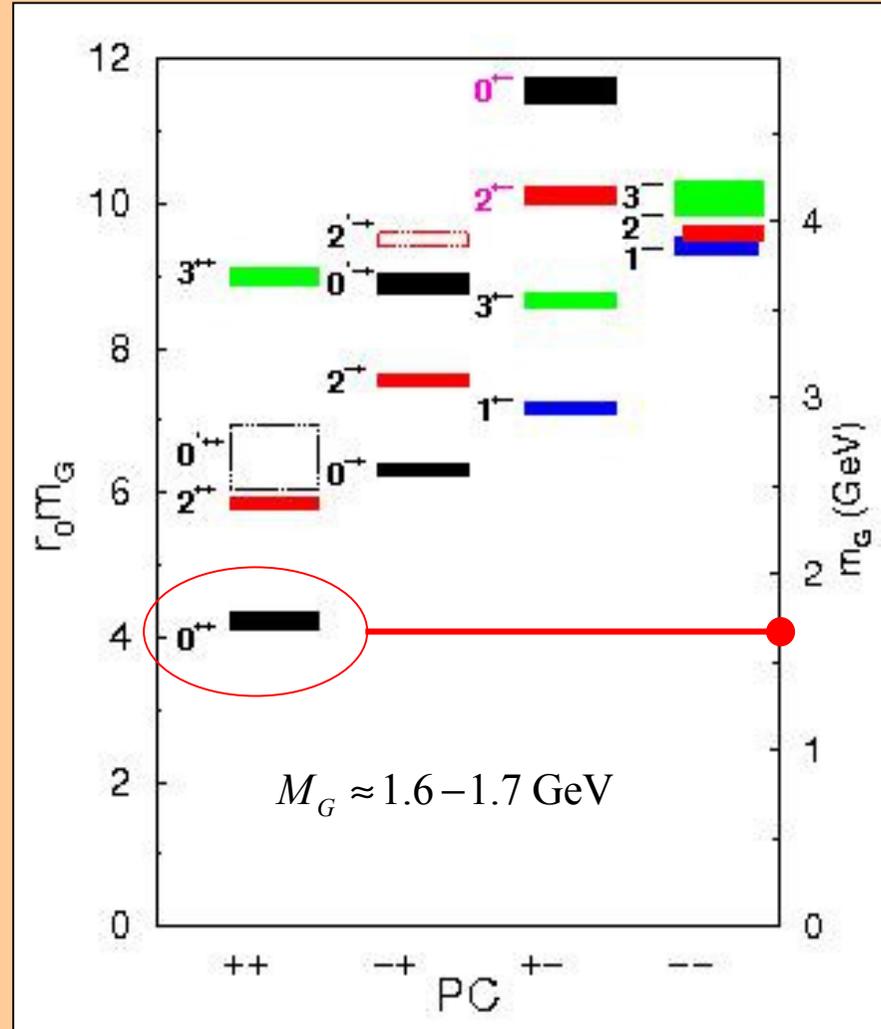
The bare glueball mass

$$\frac{M_{s\bar{s}} + M_{n\bar{n}}}{2} > M_G > M_{n\bar{n}}$$

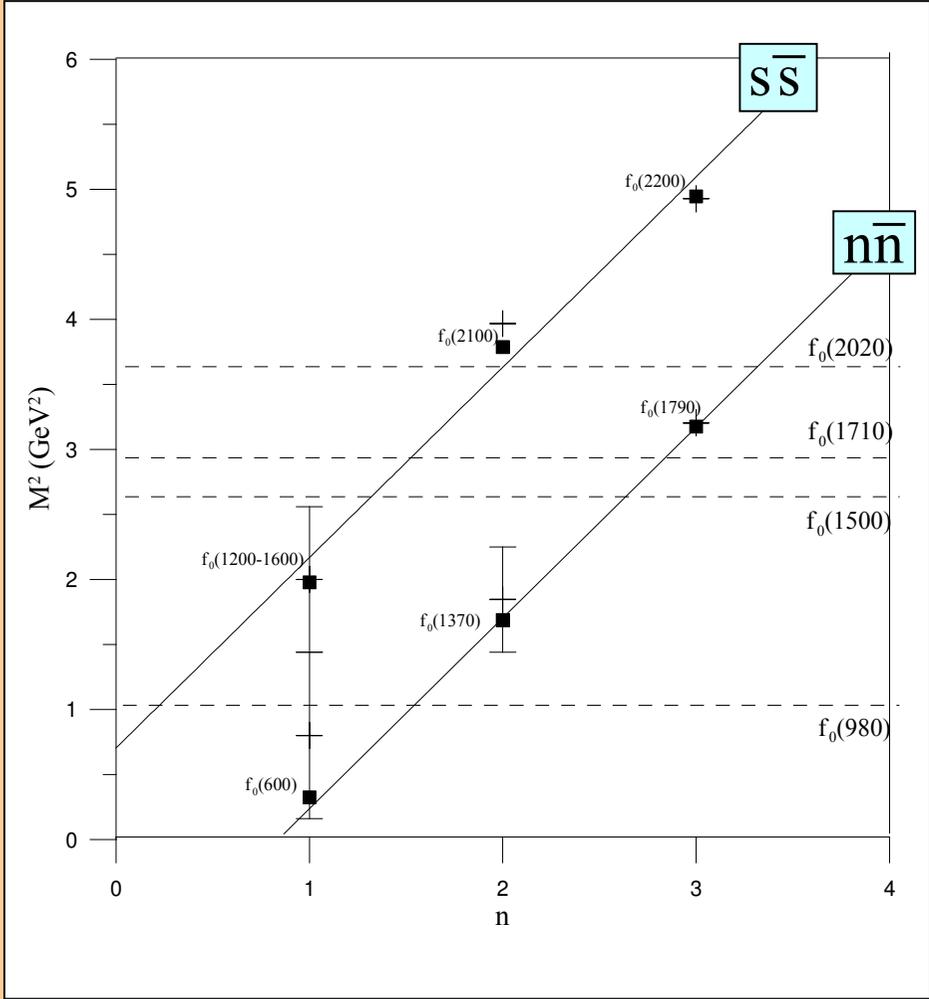
The mixing mechanism

$$\langle G|O|n\bar{n}\rangle = \sqrt{2}r\langle G|O|s\bar{s}\rangle$$

$$\langle G|O|s\bar{s}\rangle \approx 64 \text{ MeV and } r \approx 1-1.2$$



Final picture of the light scalar (isocalar) mesons



CQM (MeV)	State	Exp (MeV)
568	$f_0(600)$	400-1200
999	$f_0(980)$	980 ± 10
1299	$f_0(1.2-1.6)$	1400 ± 200
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